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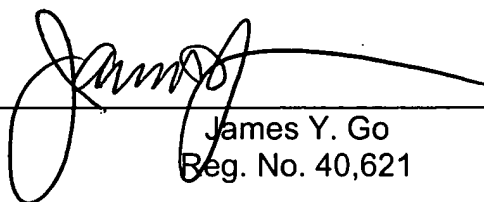
Patent

FOCUS-POSITION COMPENSATOR

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U.S. PATENT APPLICATION

FOR

5 FOCUS-POSITION COMPENSATOR

BY

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FIELD OF THE INVENTION

This invention relates to focus-position compensators for microlens arrays. More particularly, it relates to using tiles to affect the focus-position compensation.

15 BACKGROUND OF THE INVENTION

Associated with the information revolution is a need to increase by many orders of magnitude the rate of information transfer. This revolution is enabled by the switch from copper wire to optical fiber. Efficient implementation of this change requires optical switches to move data from one fiber to another. For a large number of input and a large number of output fibers, this switch is typically referred to as an optical crossbar switch.

20 A typical component of an optical crossbar switch is a fiber array coupled to a microlens array in such a way that an array of substantially collimated and parallel beams leave the assembly. A schematic of a microlens array is illustrated in FIG. 1. Each microlens array 100 is comprised of a plurality of lenslets 110. In the typical case, each optical fiber is associated with a single lenslet 110.

25 A one-to-one mapping exists between fibers and optical beams leaving the assembly. The system performance is enhanced if each optical beam is substantially focused on the end of its respective optical fiber. The construction of such a system is simplified if all of the

beams focus through the microlens array at substantially the same distance. In such a case, the ends of all the optical fibers are arranged on a plane that is a uniform distance from the microlens array. This requires that the microlens array have a high degree of uniformity with respect to the distance at which each lenslet focuses.

5 Manufacturing a microlens array with sufficiently high uniformity with respect to the focus distance is expensive. Most often, the problem is associated with variations in the focal length of the individual lenslets. However, for the purposes of this patent document, variations in the focus or focus distance can be due to focal-length variations of the lenslets or any other source of nonuniformity. In more affordable microlens arrays the focus distance
10 tends to vary slowly across the array. A typical variation is illustrated in FIG. 2. For this particular microlens array, the low regions 120 indicate portions of the microlens array for which the focus distance is as much as 3% less than the nominal value. The high regions 130 indicate portions of the microlens array for which the focus distance is as much as 4% greater than the nominal value.

15 To reduce the cost of an optical crossbar switch and maintain satisfactory performance, a means for compensating for the microlens focus variations needs to be developed.

20 SUMMARY OF THE INVENTION

Embodiments of the invention include a variety of focus-position compensators for reducing the focus variations of a microlens array. For the purposes of this application, reducing the focus variations is to be interpreted broadly. The reduction in variations can be associated with reduced maximum variations, reduced mean-square variations, reduced root-
25 mean square variations, or some other rational measure of focus variations.

Focus-position compensators of the present invention include a plurality of tiles. Each tile has its index of refraction and its thickness chosen to obtain a specified tile focus-

position adjustment or correction. The tiles are disposed in relation to the microlens array such that the effects of focus variations of the microlens array are reduced.

The invention also includes methods for making focus-position compensators for a microlens array. To practice the method, the spatial variation of focus distances of the microlens array is determined. To reduce the spatial variation of the focus distances to within a desired limit, tiles are placed in the light path between the microlens array and optical fibers. The number of tiles, the spatial distribution of tiles, and the tile focus-position corrections are chosen. For each tile, the tile focus-position correction is a function of the tile thickness and the tile refractive index; hence these properties are selected for each tile.

A reference thickness is chosen that is greater than or equal to the maximum of all the tile thicknesses. Spacer-block thicknesses are determined for all the tiles. The spacer-block thickness is equal to the difference between the reference thickness and the tile thickness. The tiles are constructed, each having its specified thickness and refractive index. All spacer blocks with non-zero spacer-block thickness are constructed.

A tile tray having a receptacle for receiving each tile is micromachined. The receptacles are positioned so that when populated with tiles, each tile will be properly situated relative to the other tiles.

The spacer blocks and tiles are placed in their receptacles. If the corresponding spacer block exists (i.e., the spacer block has non-zero thickness) then the tile is placed on top of the spacer block. For tiles that don't have a corresponding spacer block, the tile is simply placed into its receptacle.

A curable bonding material is placed on top of each tile. An intervening structure is placed on the curable bonding material. The intervening structure can be the substrate of the microlens array, a fiber-block window attached to optical fibers, or a window otherwise disposed between the optical fibers and the microlens array. The bonding material is then cured, securing the tiles to the intervening structure. The tile tray and spacer blocks are then removed.

In lieu of the curable bonding material, adhesive free bonding or fusion bonding may be used to bond the tiles to the intervening structure.

Additional features and advantages of the invention will be set forth in part in the description that follows, and in part will be obvious from the description, or may be learned
5 by practice of the invention. Various embodiments of the invention do not necessarily include all of the stated features or achieve all of the stated advantages.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings illustrate a complete embodiment of the invention
10 according to the best modes so far devised for the practical application of the principles thereof, and in which:

FIG. 1 shows a microlens array.

FIG. 2 illustrates a typical focal length variation induced focus-distance variation
across a microlens array.

15 FIGs. 3A-B show contour plots of the focus distance before and after application of tiles. FIG. 3A shows the example situation prior to the application of tiles. FIG. 3B shows the same case after the application of tiles.

FIGs. 4A-C show different embodiments of the invention. In FIG. 4A, the tiles are affixed to the substrate of the microlens array. In FIG. 4B, the tiles are affixed to a window
20 between the fiber array and the microlens array. In FIG. 4C, the tiles are affixed to the fiber-block window.

FIGs. 5A-D illustrate aspects of some steps in making a focus-position compensator according to the invention. FIG. 5A is an example microlens array. FIG. 5B shows a tile tray. FIG. 5C shows different thickness tiles in the receptacles of the tile tray. FIG. 5D
25 shows the microlens array with the focus-position compensator.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Referring now to the drawings, where similar elements are numbered the same, FIG. 1 depicts a microlens array 100 comprised of lenslets 110 (only one of which is labeled). As shown in FIG. 2, the focus distance of the microlens array is typically not uniform. However, in many instances the focus distance varies slowly across the microlens array, hence regionally compensating for focus variations can significantly reduce the variation. The present invention employs the use of tiles to produce regional focus-position compensations.

Preferred embodiments of a focus-position compensator include a plurality of tiles. Each tile has a tile refractive index n_i and a tile thickness t_i where i is a unique designator for each tile. The tile refractive index for each tile is substantially uniform over the tile. Similarly, the tile thickness for each tile is substantially uniform over the tile. The tile refractive index and the tile thickness are chosen to obtain a tile focus-position correction Δ_i . Because of the substantial uniformity of the tile refractive index and the tile thickness over the tile, the tile focus-position correction is itself substantially uniform over the tile.

The tile focus-position correction is chosen to reduce the effects of the focus variation of the microlens array. Once the focus variation of the microlens array is known, appropriate focus distance increases can be mapped to each region of the microlens array, with a tile corresponding to each region. The tile is disposed in relation to the microlens array such that the effects of focus variations of the microlens array are reduced. The spatial relationship between the tiles and the microlens array should ensure that the tiles are in the light path between the lenslets and the target of the substantially collimated light.

In most instances, the microlens array is rectangular; hence tiles having a rectangular planform are preferred. However, the broad scope of the invention is intended to include microlens arrays that are not rectangular and also tiles that do not have rectangular planforms, even if the microlens array is rectangular.

A simple example is illustrated in FIGs. 3A-B. FIG. 3A shows contours of the focus distance of a microlens array. For simplicity, the focus distance is shown as a continuous variable. In reality, each lenslet has its own focus distance, so focus distance only has meaning at the discrete lenslets. However, with a dense microlens array, where the focus

distance varies slowly from lenslet to lenslet, a continuous function is a good approximation to the actual situation. In this example, the focus distance varies according to the equation $f = 4.8 \text{ mm} + 0.02 (0.5 x + y)$, where x and y are measured in mm. This means that at position $x = 0, y = 0$, the focus distance is 4.8 mm but as x and y increase, the focus distance increases linearly. In the middle of the microlens array at $x = 10 \text{ mm}$ and $y = 5 \text{ mm}$, the focus distance is $4.8 \text{ mm} + 0.2 \text{ mm} = 5.0 \text{ mm}$. At the upper right edge of the microlens array at $x = 20 \text{ mm}$ and $y = 10 \text{ mm}$, the focus distance is $4.8 \text{ mm} + 0.4 \text{ mm} = 5.2 \text{ mm}$. Therefore the focus distance varies 4% higher and lower than its central value of 5.0 mm.

Suppose that four tiles are chosen to correct the effects of the microlens focus variation. For simplicity, each tile will be rectangular and will have nominal dimensions of 10 mm in the x direction and 5 mm in the y direction. The tiles are evenly spaced on the microlens array as shown in FIG. 3B. As discussed later, in practice, gaps will probably exist between each tile. Even if the tiles are assembled so that no gap exists, the focus-position correction can be discontinuous at the tile boundaries; hence the tile boundaries are preferably aligned with boundaries between lenslets. In this example, a focus-position correction of 0.3 mm is used for the lower-left tile; 0.2 mm for the top left and lower right tiles; and 0.1 mm for the tile at the top right. The focus position for light incident at the center of each tile is now corrected in such a way that the maximum focus variation is only 0.1 mm, or slightly less than 2%, similar to a microlens array with a focal length of $5.2 \pm 0.1 \text{ mm}$.

Alternatively, a focus-position correction of 0.2 mm could be used for the lower-left tile; 0.1 mm for the top left and lower right tiles; and no correction for the tile at the top right. The focus position for light incident at the center of each tile would now be similar to a microlens array with a focal length of 5.1 mm and the maximum variation would remain 0.1 mm. Whether the original or alternative correction scheme is used will depend upon factors specific to each application of the invention. Both correction schemes are considered to be within the scope of the invention.

The focus-position corrections can be achieved by adjusting the tile thickness, the tile refractive index, or both. In most cases, the focus-position correction is related to these parameters by the equation: $\Delta_i = t_i (1 - n_{\text{media}}/n_i)$, where n_{media} is the refractive index of the media that the tile is supplanting. For most cases of practical interest, the media is air, some inert atmosphere, or a vacuum. Generally, n_{media} can be approximated as 1 in those cases. Other appropriate relationships between the focus-position correction, the tile thickness, the tile refractive index, and the index of refraction of the external media, as well as other relevant parameters may be used when required by the situation.

In the original scheme of the previous example, taking $n_{\text{media}} = 1$, all of the tiles could have been made with thickness 0.6 mm. In this case, to achieve a 0.3 mm focus-position correction, the tile in the lower left would require a refractive index of 2. The tiles in the upper left and lower right would require a refractive index of 1.5 to achieve a 0.2 mm focus-position correction. To achieve a 0.1 mm focus-position correction, the tile in the upper right would require a refractive index of 1.2.

Alternatively, in the previous example with $n_{\text{media}} = 1$, all of the tiles could have been made of a material having a refractive index of 1.5. In this case, the tile in the lower left would need to be 0.9 mm thick, the upper left and lower right tiles would need to be 0.6 mm thick, and the upper right tile would be 0.3 mm thick. Clearly, combinations of different tile refractive indices and thicknesses can be used to achieve the desired focus corrections.

A large number of materials may be used to obtain the desired properties of the tiles. Clearly index of refraction is important, but uniformity of the material, cost, ease with which it can be machined and handled, scratch resistance, etc. are just some of the other material properties that might influence which material is best suited for a specific tiling application. Some materials that are believed to be useful for tiles include: glass, sapphire, fused silica, calcite, quartz, Calcium Fluoride, Magnesium Fluoride, Zinc Selenide, Zinc Sulfide, Germanium, Silicon, Gallium Arsenide, Gallium Phosphide, Aluminum Gallium Arsenide, Indium Gallium Arsenide, and KRS5 (an infrared window material that contains Tellurium Bromide Tellurium Iodide).

The tiles may be affixed to a variety of intervening structures to effect the focus correction. The term intervening structure is used because the structure is placed between the lenslets and the target for the collimated light. FIGs. 4A-C show side views of three different intervening structures.

5 In the embodiment illustrated in FIG. 4A, each lenslet **110** of the microlens array **100** is supported in a substrate **150**. The light from each lenslet **110** is to be focused to a corresponding optical fiber **170**, which is supported in a fiber block fiber holder **210** and covered by a fiber block window **180**. The fiber block fiber holder **210** comprises one or more elements that support the optical fibers **170**. The fiber block fiber holder **210** includes
10 any appropriate means for supporting the optical fibers that is known to those skilled in the art. The plurality of optical fibers **170** attached to the fiber-block fiber holder **210** and covered by the fiber block window **180** is known as the fiber array **160**. In this embodiment, each tile **200** is affixed to the substrate **150** of the microlens array **100**. Although the tiles **200** are shown as having variable thickness, as discussed earlier, they may instead and/or also
15 have variable refractive indices to achieve the desired focus correction. Note that to avoid clutter in the figure, although many lenslets, optical fibers, and tiles are shown, only one of each is explicitly labeled.

FIG. 4B illustrates an embodiment in which a window **190** serves as the intervening structure to which the tiles **200** are affixed. FIG. 4C shows an embodiment in which the tiles
20 **200** are affixed to the fiber-block window **180** of the fiber array **160**. Other embodiments that fall within the broad scope of the claims are also considered as part of the invention. For instance, some of the tiles can be affixed to the substrate **150** and others to the fiber-block window **180**.

A variety of fastening techniques may be employed to affix the tiles to the intervening
25 structure. In some preferred embodiments a bonding material is used. In the most preferred of these embodiments a curable bonding material is used. Most preferably, UV (ultraviolet) curing cement is used to affix the tiles to the intervening structure. Alternatively, adhesive

free bonding (of which fusion bonding is a specific example) may also be used to affix the tiles to the intervening structure.

Because of the typically large difference in refractive index between the tiles and the external media, an antireflection coating is often added to the side of the tiles that is not affixed to the intervening structure, i.e., the side exposed to the external media. Refractive index variations between the tiles and the intervening structure are typically not so large, hence antireflection coatings are not usually employed at that interface.

The construction of focus-position compensators corresponding to the present invention can be accomplished by separately bonding each tile in its proper position. However, the invention also includes more efficient methods for making focus-position compensators for a microlens array.

To practice these methods, the spatial variation of the focus distance for the microlens array needs to be determined. One way to determine the focal length variation is with a Zygo Microtopi. A Zygo Microtopi is an instrument that can measure the exact curvature of each lenslet in a microlens array. From the curvature, the focal length of the individual lenslets is calculated using techniques known to those skilled in the art. Any additional alterations to the focus distance associated with each lenslet can then be added to the computed focal length. Knowledge of the focus distance of each lenslet is used to determine the spatial variation of the microlens focus distances. Other approaches for determining the focus variation can also be used including, for example, a Hartmann sensor.

The number of tiles, the spatial distribution of tiles, and the tile focus-position correction Δ_i of the i -th tile are chosen such that the focus variation of the microlens array is reduced to within a desired limit. The best choice for all of the parameters depends upon the details of each case.

The tile thickness t_i and tile refractive index n_i are selected to achieve the desired tile focus correction Δ_i . As discussed earlier, a useful formula that relates the focus correction, the thickness and the refractive index is $\Delta_i = t_i (1 - n_{\text{media}}/n_i)$, where n_{media} is the refractive

index of the media that the tile supplants. Other relationships may be used as appropriate to determine the best choice of parameters for any given situation.

After all the tile thicknesses are known, a reference thickness t_{ref} is chosen. The reference thickness should be greater than or equal to the maximum tile thickness. The reference thickness is used to determine spacer-block thicknesses. The thickness of each
5 spacer block is designated s_i and is determined by $s_i = t_{ref} - t_i$.

The tile and spacer block thicknesses are constructed to have their appropriate shapes and sizes. To reduce costs, in preferred embodiments, the tiles are cut from sheets of material that are obtained in the desired thicknesses. The sheets may be of any appropriate tile
10 material. Silica or glass is used in the most preferred embodiments although, as discussed earlier, many other materials are suitable. The spacer blocks can be similarly constructed. If any of the spacer blocks has zero thickness (i.e., $s_i = 0$) then that spacer block is not necessary.

A tile tray having a receptacle for receiving each tile needs to be micromachined.
15 Each of the receptacles is positioned to receive its corresponding tile. In preferred embodiments the tile tray is constructed of Silicon and is micromachined with a deep reactive ion etching (DRIE) process. The use of the tile tray greatly facilitates tile alignment, especially when many tiles are used.

All spacer blocks having finite thickness (i.e., $s_i > 0$) are placed in their respective
20 receptacles. Each tile is placed on top of its corresponding spacer block where one exists (i.e., $s_i > 0$). For tiles with no corresponding spacer block, the tiles are just placed in their respective receptacles. Note that because of the way in which the spacer block thicknesses are determined, the sum of the tile thickness and the spacer-block thickness is always the same and equals t_{ref} . This means that the top of all the tiles are at the same height.

25 The desired intervening structure is placed on top of the tiles, aligned and bonded. The order in which this is done depends, in part, upon the type of intervening structure. As discussed earlier, in preferred embodiments the intervening structure is a substrate of the

microlens array, a fiber-block window, or a window placed between the microlens array and a plurality of optical fibers.

In the case in which the intervening structure is the substrate of the microlens array or a fiber-block window, the tile tray is aligned after the intervening structure is placed on top of the tiles but prior to bonding. In the case in which the intervening structure is the substrate of the microlens array, the tile tray is usually aligned with the microlens array using X-Y positioners and a rotation stage to set the correct clocking angle. The alignment is most easily accomplished under a microscope. In preferred embodiments the alignment process tries to ensure that the tile boundaries occur between the lenslets, so that the light from a lenslet does not pass close enough to the tile boundary to become significantly distorted. A similar alignment is performed in the case in which the intervening structure is the fiber-block window. In this case, the tile tray is aligned with the optical fibers, again trying to ensure that a minimum amount of light is distorted by the tile boundaries. In preferred embodiments, the alignment is accurate to about 0.01 mm.

Any appropriate bonding process known to those skilled in the art may be used. Some preferred embodiments employ adhesive free bonding, including, fusion bonding. Other preferred embodiments employ a curable bonding material, most preferably, UV curing cement.

In cases in which a curable bonding material is used, the curable bonding material is placed on top of each tile and then the desired intervening structure is placed on top of the curable bonding material. In the case of UV curing cement, the curing involves exposure to ultraviolet radiation.

After the tiles are bonded, the tile tray and the spacer blocks are removed. The tiles are now affixed to the intervening structure. In cases in which the intervening structure is a window disposed between the microlens array and the optical fibers, the window must be aligned with the microlens array and the optical fibers. This is typically, but not necessarily done after the tiles are bonded to the intervening structure.

As a detailed example, consider a microlens array containing 1200 lenslets arranged in 30 rows of 40 lenslets each. Except that somewhat larger and fewer lenslets are shown FIG. 5A is illustrative of the example microlens array 100. Only a single lenslet 110 is labeled to reduce clutter in the figure. The lenslets 110 in this example are arranged with a 1-mm pitch, meaning that the lenslet centers are separated by 1 mm in each row and each column. Each lenslet 110 is approximately 0.95 mm in diameter, so they are separated from their nearest neighbors by approximately 0.1 mm. A 2.5-mm border 140 extends around the edges of the microlens array 100 in this example.

The spatial variation of the microlens array focus distance is determined. Four tiles, each with a refractive index of approximately 1.5 are to be used. Each tile has a rectangular planform with nominal dimensions of 15 mm by 20 mm. Three different tile thicknesses are to be used 0.129 mm, 0.258 mm, and 0.516 mm. These will produce focus-position corrections of 0.043 mm, 0.086 mm, and 0.172 mm, respectively. In this case the reference thickness is chosen as 0.516 mm; hence only three spacer blocks are required, two having a thickness of 0.258 mm and one having a thickness of 0.387 mm. Because one of the tiles has a thickness equal to the reference thickness, the corresponding spacer-block thickness is zero; therefore no corresponding spacer block is used. Although the thicknesses are defined to three significant figures, deviations in the thicknesses of as much as ± 0.01 mm have been determined to be acceptable in this example.

Although the tiles are nominally 15 mm by 20 mm, to adequately support them in a tile tray requires that they be somewhat smaller. In this example, the tiles and the spacer blocks are cut to 14.925 mm by 19.925 mm with acceptable errors of ± 0.015 mm. Note that this implies that the tiles will be separated by a gap. Providing that the collimated light beam remains sufficiently far from the edge of the tile, the gaps are not problematical.

FIG. 5B shows a schematic of the tile tray 300. The starting material for the tile tray is a piece of Silicon 35 mm by 45 mm by 1.5 mm. Four rectangular receptacles 320 are micromachined in the Silicon using DRIE. These regions are 14.950 mm by 19.950 mm with a tolerance of ± 0.005 mm. The receptacles are 0.450 mm deep. A 2.5-mm border 310 is

maintained around the edge of the tile tray **300** to conform to the border **140** around the edge of the microlens array **110** (as seen in FIG. 5A).

5 The three spacer blocks are inserted into their respective receptacles in the tile tray. Note that each one lies at the bottom of its receptacle. The four tiles are placed into their respective receptacles. Three of the tiles overlies spacer blocks; the 0.516 mm thick tile lies at the bottom of its receptacle. FIG. 5C shows the tiles **200** in the tile tray **300**.

10 In this example, UV curing cement (for example, Norland 61) is placed on top of the tiles. The substrate of the microlens array is placed on top of the tiles. Under a microscope, using X-Y positioners and a rotation stage to set the correct clocking angle, the tile tray is aligned with the microlens array to within 0.01 mm.

After alignment, ultraviolet radiation is used to cure the cement. The tile tray and spacer blocks are then removed. The finished product is schematically shown in FIG. 5D. The tiles **200** overlay the substrate (transparent) of the microlens array **100**. The lenslets **110** can be seen through the tiles **200**.

15 The above description and drawings are only illustrative of preferred embodiments, and the present invention is not intended to be limited thereto. Any modification of the present invention that comes within the spirit and scope of the following claims is considered part of the present invention.